Multi-hop whistler-mode ELF/VLF signals and triggered emissions excited by the HAARP HF heater

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[1] Modulated heating of the lower ionosphere with the HAARP HF heater is used to excite 1–2 kHz signals observed on a ship-borne receiver in the geomagnetic conjugate hemisphere after propagating as ducted whistler-mode signals. These 1-hop signals are believed to be amplified, and are accompanied by triggered emissions. Simultaneous observations near (~30 km) HAARP show 2-hop signals which travel to the northern hemisphere upon reflection from the ionosphere in the south. Multiple reflected signals, up to 10-hop, are detected, with the signal dispersing and evolving in shape, indicative of re-amplification and re-triggering of emissions during successive traversals of the equatorial interaction regions. *INDEX TERMS:* 2403 Ionosphere: Active experiments; 2483 Ionosphere: Wave/particle interactions; 2736 Magnetospheric Physics: Magnetosphere/ionosphere interactions; 2794 Magnetospheric Physics: Instruments and techniques. **Citation:** Inan, U. S., M. Gołkowski, D. L. Carpenter, N. Reddell, R. C. Moore, T. F. Bell, E. Paschal, P. Kossey, E. Kennedy, and S. Z. Meth (2004), Multi-hop whistler-mode ELF/VLF signals and triggered emissions excited by the HAARP HF heater, *Geophys. Res. Lett.*, *31*, L24805, doi:10.1029/2004GL021647.

1. Introduction

[2] Electromagnetic waves in the 4 Hz to 6.5 kHz range are known to be generated by modulated HF heating of the lower ionosphere through which auroral electrojet currents flow [*Barr and Stubbe*, 1984; *Villaseñor et al.*, 1996]. ELF/VLF waves have been generated at the High Frequency Active Auroral Research Program (HAARP) in Gakona, Alaska using HF heating modulated at ELF/VLF, under a wide range of geomagnetic conditions (R. C. Moore et al., ELF/VLF waves generated by an artificially modulated auroral electrojet above the HAARP HF heater, submitted to *Journal of Geophysical Research*, 2004, hereinafter referred to as Moore et al., submitted manuscript, 2004). HAARP is located at $L \simeq 4.9$, where the magnetic field lines are usually dipole-like and tend to lie within or near the plasmaspause. HAARP is thus well positioned for use in controlled wave-injection experiments to study ELF/VLF wave growth and emission triggering, similar to those conducted during 1973–88 with the Siple Station, Antarctica VLF transmitter ($L \simeq 4.2$). Siple Station [*Helliwell*, 1988] consisted of a ~100 kW transmitter (later ~150 kW) driving a 21 km horizontal antenna (later extended to 42 km crossed dipoles) placed on an ice sheet ~2 km in thickness. The transmitter launched ~1.6 to 5 kHz waves on field lines ranging from $L = 3$ to $L = 5$ observed at receivers in the geomagnetically conjugate region in Canada, with ducting, amplification, and emission triggering occurring in many cases. We report here the first observations of the excitation by an HF heater of ducted whistler-mode ELF/VLF signals, amplified in the magnetosphere and accompanied by triggered emissions (Figure 1).

2. Review of HF Heater ELF/VLF Generation

[3] The EISCAT HF heater near Tromsø, Norway has been used to generate ELF/VLF signals [*Stubbe et al.*, 1982; *Barr and Stubbe*, 1984, 1991; *Rietveld et al.*, 1989] with amplitudes of ~1 pT on the ground. With a total radiated HF power of 1 MW and effective radiated power (ERP) of 200–300 MW at 2.75 to 8 MHz, the Tromsø heater was often 100% amplitude modulated with a square wave. Tromsø is located at $L > 6$, and is thus on sub-auroral/auroral field lines on which conditions for hemisphere-to-hemisphere ducting are less favorable [*Carpenter and Sulic*, 1988]. HF ionospheric heaters at Arecibo, HIPAS, and HAARP have been used to modulate ionospheric current systems. At Arecibo, 500 Hz to 5 kHz waves were produced using ~3 MHz with a total HF input power of 800 kW, and an ERP of 160–320 MW [*Ferraro et al.*, 1982]. The HF heater may have sometimes created field aligned ducts [*Starks et al*, 2001]. At HIPAS, ELF/VLF waves were created using amplitude and phase modulation, most successfully when the electrojet was in the path of the HF beam, when there was low D region absorption, and when energetic particle precipitation and visible aurora were not overhead [*Villaseñor et al.*, 1996]. ELF/VLF wave generation at HAARP was found to be most efficient [*Milikh et al.*, 1999] for ~3.3 MHz in X-mode with 100% square wave modulation.

3. Experimental Setup

3.1. The High Frequency Active Auroral Research Program (HAARP)

[4] The HAARP HF heater is located at ~62.4°N and 145.2°W geographic (63.1°N and 92.4°W geomagnetic). A high power, HF phased-array transmitter is used to heat small, well-defined volumes of the ionosphere (see:

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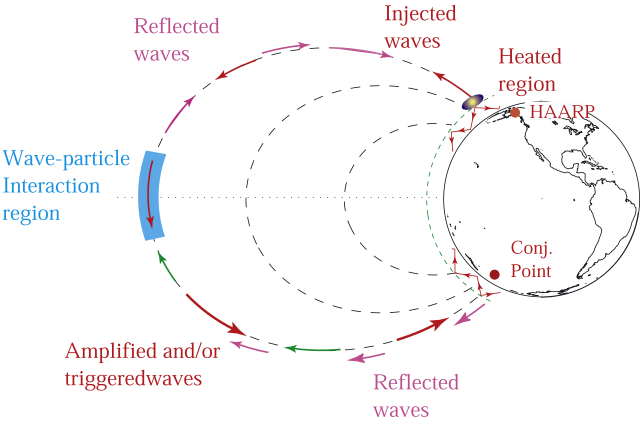

Figure 1. Schematic of ducted whistler-mode propagation excited by the HAARP HF heater.

www.haarp.alaska.edu). The transmitter had a total radiated HF power capability of 960 kW at the time of the observations. HF carriers of 3.25 MHz and 5.8 MHz were used, with the ELF/VLF signal format impressed as 100% sinusoidal amplitude modulation.

3.2. ELF/VLF Receivers

[5] The ELF/VLF receivers utilized large square (4.8 m by 4.8 m) or triangular shipboard (4.2 m high with 8.4 m base) air core antennas, with terminal resistive and inductive impedances respectively of 1-Ω and 1-mH, matched to a low-noise (noise figure of ∼2–3 dB at a few kHz) preamplifier with a flat frequency response (∼300 Hz to ∼40 kHz). The data in the north were acquired at Chistochina, Alaska, within ∼35 km of HAARP. Observations in the south were conducted on the research vessel *Tangaroa*, while it was near (within ∼100 km) the geomagnetically conjugate point of HAARP, to deploy a buoy for autonomous ELF/VLF measurements of 1-hop ducted whistler-mode signals excited by HAARP.

4. Observations

[6] Between 0200UT and 1500UT each day from April 19 to April 26, 2004, HAARP transmitted continuously, repeating a 1-minute long ELF/VLF modulation consisting of a sequence of frequency-time ramps, pulses, and chirps. HF transmissions were in the X-mode, alternating between 3.25 MHz and 5.8 MHz every 30-minutes, operating at full power (960 kW), with the HF beam oriented vertically.

[7] The multi-hop ducted whistler-mode signals were observed on 20 April 2004 between 0310 and 0345 UT. No evidence for whistler-mode echoes was observed in either hemisphere outside of this ∼1 hour period. Figure 2 shows two well defined examples of 1-hop signals observed on the *Tangaroa*, located at 55.38°S and 174.65°E ($L \simeq 4.5$). The top panel shows relatively weak HAARP transmitted frequency-time ramps and pulses observed at Chistochina in addition to natural activity in the range ∼1 to ∼2 kHz. The second and third panels show *Tangaroa* data during the first 15 seconds of two successive minutes. The 1-hop signal is visible at the same time on both panels. The repeated occurrence of this signal at the same time (in the two minutes shown and in others not shown) is clear evidence of a causal connection to the HAARP transmissions. The

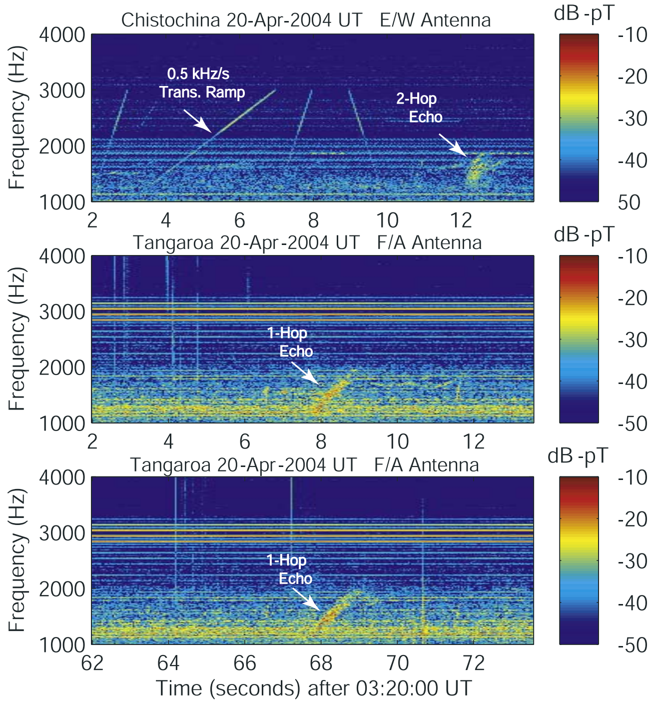

Figure 2. Spectrograms showing 2-hop and 1-hop echoes received at Chistochina, Alaska (top panel) and at the magnetic conjugate point on the *RV Tangaroa* (two bottom panels).

steepening of the frequency-time slope of the 1-hop signal with respect to that of the transmitted ramp (visible in the top panel) is generally consistent with whistler-mode dispersion (in this case leading to signal compression) from ∼1 to ∼2 kHz. These frequencies are below the so-called 'nose' frequency of fastest travel [*Helliwell*, 1965, p. 32] at the inferred *L*-shell of ∼4.9. Figure 2 (top panel) also shows the 2-hop echo, delayed (at each frequency) from the 1-hop (on the *Tangaroa* records) by as much as the 1-hop signal is

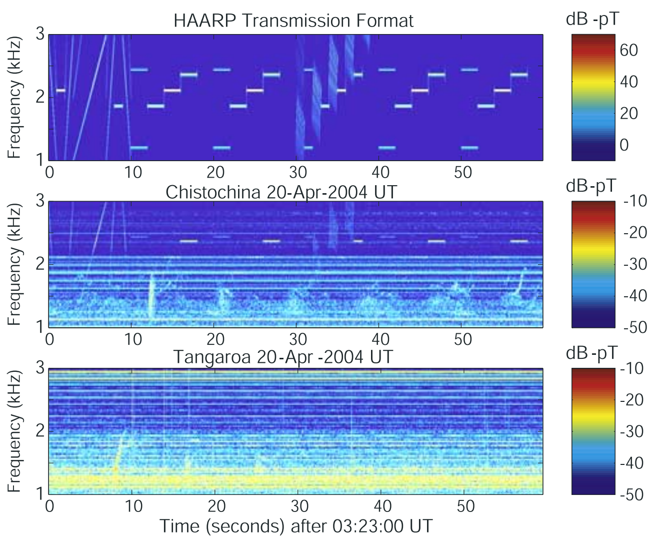

Figure 3. Spectrograms showing HAARP transmission format (top panel), echoes recorded at Chistochina (middle panel) and echoes recorded on the *RV Tangaroa* (bottom panel).

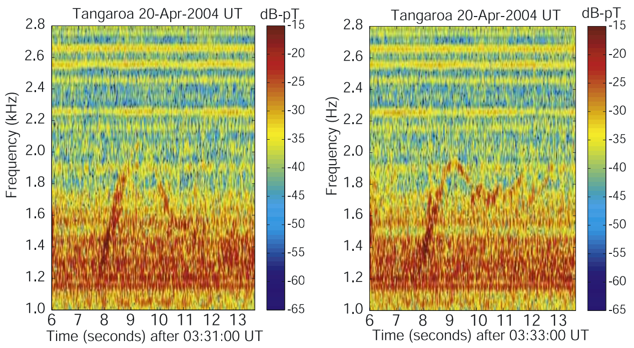

Figure 4. 'Hook' emissions triggered by 1-hop ramp signals.

delayed with respect to the parent frequency-time ramp. The increased steepness of the 2-hop signal is consistent with the further dispersion (leading to compression in time) upon its second traverse of the field line path. The diffuseness of both the 1-hop and 2-hop traces is indicative of wave-growth (amplification) and the triggering (and retriggering during each equatorial traverse) of emissions, combined with multi-path propagation [*Helliwell*, 1988].

[8] Figure 3 shows a 1-min record from the same hour. The ELF/VLF frequency-time format transmitted is evident in the top panel, showing Chistochina data from an earlier campaign when the ELF/VLF signals were exceptionally strong and well defined, as is also evidenced by the presence of harmonics resulting from the non-linear nature of the ELF/VLF generation in the ionosphere. Evident in the middle panel of Figure 3 is the 2-hop signal similar to the one seen in the top panel of Figure 2, as well as additional hops (4th, 6th, 8th, and 10th).

[9] Although the *Tangaroa* data are noisy due to the hum on the ship, a few of the 1-hop signals showed evidence of the triggering of 'hook' emissions, as shown in Figure 4. These emissions repeat in multiple minutes in time association with the 1-hop ramp and exhibit the hook-like frequency-time signature that is one of the known forms of triggered VLF emissions [*Helliwell*, 1965, p. 209]. When initiated by Siple transmitter signals in this region ($4 < L < 5$), such emissions are typically preceded by temporal growth of 10–30 dB [*Helliwell*, 1988]. The observation of triggered emissions is thus strong evidence of amplification of the injected signals in high altitude interaction regions.

[10] The absolute magnitudes of the HAARP 1-hop signal and multi-hop echoes were ~0.01 pT to 0.1 pT, substantially smaller than the typical values of HAARP signals of ~1 to ~10 pT observed at Chistochina (Moore et al., submitted manuscript, 2004). While the locally observed 'parent' signals were even weaker, comparing the amplitudes of the locally observed signals with the absolute amplitudes of the 2-hop and higher order echoes does not necessarily allow a determination of the magnetospheric amplification of the injected ELF/VLF signals. The altitude distribution of the heated electrojet currents that radiate the ELF/VLF signal is not known and is dependent on the altitude profiles of electron density and electrical conductivity, and the magnitude and altitude distribution of the electric field.

[11] During the ~1 hour period of observation of the multi-hop whistler-mode signals, the HF carrier frequency was switched from 3.25 MHz to 5.8 MHZ with little discernable difference in the magnetospheric response. No significant differences were found in the properties of HAARP ELF/VLF signals received on the high altitude CLUSTER satellites [*Platino et al.*, 2004] for HF carrier frequencies of 3.2 MHz versus 5.8 MHz. The whistler-mode echoes were observed during daylight hours, 1900–2000 HAARP local time, more than an hour before sunset, which on April 20th occurred at approximately 2124 local time.

[12] Whistler-mode signal amplification may often be limited to an 'active' (and sometimes narrow) frequency range that is dependent upon the distribution of interacting electrons and may also be located close to a band of natural wave activity [*Sonwalkar et al.*, 1997; *Carpenter et al.*, 1997]. Amplification may also be dependent upon the frequency-time slope of the injected signal, with the more gradual slopes inducing a greater response [*Carlson et al.*, 1985]. Note from Figure 3 that the only component of the transmitted modulation pattern that leads to whistler-mode echoes is a portion of the 0.5 kHz/s frequency-time ramp between ~1.2 and ~2 kHz. It is likely that the 2-s long constant-frequency pulses did not lead to echoes because the pulse at 1225 Hz was just below the active range while the pulse at 1875 Hz was close to its upper boundary. In fact, a few rather weak 1-hop signal components of the 1225 Hz pulse were observed near 0330–0331 UT.

[13] Geomagnetic conditions during the observations were generally quiet, with maximum Kp being 2^- during the past 24 hours, although conditions were disturbed (maximum Kp of 3^+ and 4^-) on April 16th and less so (maximum Kp of 3^-) on the 17th through the 18th. Calibrated auroral electrojet (A*E*) indices are not yet available but preliminary results show calm conditions, consistent with magnetometer readings from the HAARP site showing deviations from baseline of <30 nT.

5. Interpretation

[14] Whistler-dispersion analysis was used to determine the L-shell of propagation and the equatorial cold plasma density. The time delay (at each frequency over the range of ~1 to ~2 kHz) between the time of origin of the original frequency-time ramp signal and the leading edge of the echo was measured. The measured data points were extrapolated to determine the 'nose' frequency f_n of minimum time delay and hence f_{Heq}, the equatorial gyrofrequency along the field line, through the relation $f_n \simeq 0.4 f_{Heq}$ [*Sazhin et al.*, 1992]. The measured values were then used together with a diffusive equilibrium model of the cold plasma distribution along the field line [*Angerami and Thomas*, 1964] to infer the equatorial electron density N_{eq}. This analysis revealed values of $L \simeq 4.9$ and $N_{eq} \simeq 280$ cm^{-3}, consistent with the empirical model of *Carpenter and Anderson* [1992].

[15] The frequency-time traces of the 1-hop and higher-order echoes determined by integrating the group velocity along the field line are superimposed as white traces on the spectrograms in Figure 5a, as a consistency check on the determination of L and N_{eq}. The calculated traces agree well with the leading edges of the whistler-mode hops, but the

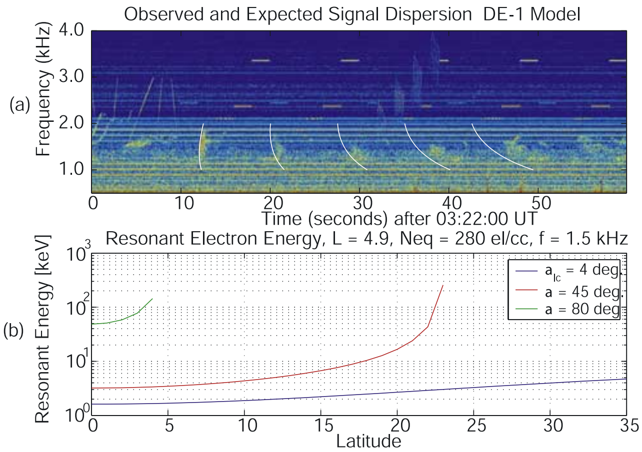

Figure 5. (a) Overlay on observed multi-hop signals traces showing expected dispersion that would be experienced by HAARP transmitted signals. (b) First order resonant electron energies for the observed data for various pitch angles.

diffuse extensions that follow the leading edges are clearly evident.

[16] With the *L*-shell of propagation and the cold plasma density determined, the energy of the electrons that would undergo first order cyclotron resonance interactions with the injected waves can be calculated [e.g., see *Chang and Inan*, 1983]. Resonant electron energy as a function of geomagnetic latitude along the field line for three different pitch angles is shown in Figure 5b. Since high-pitch-angle electrons likely drive the gyroresonance instability [*Bell et al.*, 2000], the electrons involved in the amplification of the injected waves and the triggering of emissions must have had energies of a few tens of keV.

6. Summary

[17] Observations of the excitation of ducted whistler-mode echoes by modulated HAARP HF transmissions show that controlled ELF/VLF wave-injection experiments aimed at investigating the coherent cyclotron resonance growth, amplification and emission triggering processes in the magnetosphere can be conducted with this facility. In view of the demonstrated (Moore et al., submitted manuscript, 2004) capabilities of HAARP in exciting waves over a very broad range of frequencies (from a few Hz to 30 kHz), and since the HAARP facility is currently being upgraded in radiated power by a factor of >3, such experiments can provide an excellent test bed for study of magnetospheric wave-particle interactions.

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